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Neck mobility measurement by means of the 'Flock of Birds' electromagnetic tracking system

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Abstract

Objective. To establish the accuracy and reliability of a six-degrees-of-freedom electromagnetic tracking device, the "Flock of Birds", for measuring neck rotations and to identify the main sources of error.

Design. Ten human subjects made the same types of maximal neck rotation, both actively and passively: axial rotation in neutral position, from a flexed position and from an extended position, flexion/extension and lateral flexion. The same movements were mimicked in a 'dummy head' set-up.

Methods. One Flock of Birds receiver was mounted on the thorax, one on the head. By means of a third receiver, mounted on a stylus, bony landmarks on head and thorax were palpated. These served to define two anatomically based local coordinate systems, to which the rotations were referred.

Results. Measurements were accurate with a maximal measurement error of 2.5°. No significant difference between active and passive rotation was seen. The intra-subject variation was low within the same session, SD between 2° and 4°. Between sessions the variability was considerable, SD between 5° and 16°.

Conclusion. The Flock of Birds method is reliable and sufficiently precise. The variability in measured range of motion between sessions is a point of concern in interpreting follow-up studies in patients.

Relevance

A reduced range of neck motion is a major complaint in pathologies of the cervical spine or the shoulder. A method is described in which neck rotations are related to well-defined bony landmarks. In combined rotations, e.g. flexion combined with axial rotation, the measured range of motion can sometimes fluctuate strongly (up to 30°) between measurements, without apparent pathology.

Keywords: Neck mobility; Cervical spine; 3-D angle measurement; Range of motion

1. Introduction

Measuring the range of motion of the cervical spine is an important clinical issue. Apart from insight in the total mobility, the range of motion can also be used to observe any intra- or inter-subject differences, which are important in the assessment of therapeutic interventions. In the past the maximal range of motion has been measured using optical techniques, radiography, electrogoniometry or ultrasonic techniques (Chen et al., 1999). For the accurate clinically feasible measurement of head mobility a new technique has been developed, consisting of a combination of a palpation technique with an electromagnetic tracking device, 'Flock of Birds' (FoB). In this paper we will investigate the accuracy and reliability of this instrument and assess the major sources of measurement error.

The present method measures the relative motion of the head with respect to the thorax by two FoB

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receivers, mounted on the head and the thorax, respectively. As an advantage with respect to most other methods, the motions reported do not depend on the more or less accidental mounting position of the receivers, but refer to anatomically well-defined local coordinate systems (LCS) making the measurements independent of the posture of the patient or the positioning of the receivers. To construct these coordinate systems, the relative positions of bony landmarks on head and thorax with respect to the local head or thorax receivers are palpated before the actual measurement with a third FoB receiver, mounted on a palpation stylus. The measurements from the two receivers are then recalculated to position and orientation of the head coordinate system with respect to that of the thorax. A similar combination of the palpation technique with the FoB has already been used to measure the mobility of the shoulder (Meskers et al., 1998).

2. Methods

2.1. Subjects

Ten normal subjects with no previous neck complaints, five men and five women (mean age: 39.0 SD 11.5 years) participated in this study. An informed consent was obtained from all of them in accordance with the policy statement of the American College of Sports Medicine.

2.2. Measurement system and calibrations

A six-degrees-of-freedom electromagnetic measurement system, the FoB (Ascension Technology Corporation, Burlington, USA), was used. The FoB consists of one standard range transmitter and three receivers. One of the receivers is mounted on a 65 mm stylus for palpation of the bony landmarks (Meskers et al., 1999). The other two receivers are taped on the forehead and sternum respectively. The actual measurement of the range of motion is recorded with these two receivers in continuous measurements at a measurement frequency of 50 Hz. The FoB system records both 3-D positions and orientations of the receivers relative to the transmitter, which is positioned about 0.3 m at the right side of the shoulder. In a way similar to earlier studies (Meskers et al., 1999; Day et al., 2000), the position recording was calibrated beforehand and corrected by means of calibration frame with 40 well-defined points.

2.3. Initial measurements

With the subject sitting on a chair seven bony landmarks (see Table 1) were palpated with the stylus receiver. The position and orientation of the stylus receiver were recorded together with the position and orientation of the receivers on the head and thorax. This yields the coordinates of the vectors between receivers on head or thorax and the bony landmarks (Meskers et al., 1998).

Table 1
LCS, defined with respect to bony landmarks, nosebridge (NB), chin midpoint (CH), processus xiphoideus (PX), incisura jugularis (IJ), protuberantia occipitalis externa (C0), processus spinosus of the seventh cervical spinal body (C7), processus spinosus of the eighth thoracic spinal body (T8)

Head	Origin: NB Xh: to the right, perpendicular to the plane formed by NB, CH, C0 Yh: upward, in direction of line CH-NB Zh: backwards, perpendicular to Xh and Yh
Thorax	Origin: IJ Yt: upward, parallel to a line from the mid of T8-PX to the mid of C7-IJ Xt: to the right, perpendicular to Yt and C7-IJ Zt: backwards, perpendicular to Xt and Yt

LCS were defined for head and thorax on the basis of the bony landmarks, see Table 1. These LCS systems were defined such, that the X-axes were to the right, Y-axes approximately vertical, and Z-axes directed backward. As a next step the orientations ${}^{\mathrm{H}}\mathbf{R}_{\mathrm{head}}$ and ${}^{\mathrm{Th}}\mathbf{R}_{\mathrm{thorax}}$ of head and thorax receivers with respect to their LCS were calculated and their relative positions. Neck rotations are measured by FoB as changes in orientation of the two receivers ${}^{\mathrm{G}}\mathbf{R}_{\mathrm{ech}}$ and ${}^{\mathrm{G}}\mathbf{R}_{\mathrm{ect}}$ with respect to the global coordinate system, i.e. relative to the transmitter. They are recalculated into rotations between the two LCS by:

$$\mathbf{R} = {}^{\mathrm{thorax}}\mathbf{R}_{\mathrm{head}} = {}^{\mathrm{Th}}\mathbf{R}^{\mathrm{T}}_{\mathrm{thorax}} \cdot {}^{\mathrm{G}}\mathbf{R}^{\mathrm{T}}_{\mathrm{ect}} \cdot {}^{\mathrm{G}}\mathbf{R}_{\mathrm{ech}} \cdot {}^{\mathrm{H}}\mathbf{R}_{\mathrm{head}} \qquad (1.1)$$

in which $\mathbf{R}^{\mathrm{T}}$ denotes the transpose matrix.

2.4. Axis rotation

The 3×3 rotation matrix $\mathbf{R}$ can be represented by 3 angles for which several conventions are available. It turned out that Euler or Cardan angles could not represent all rotations used in this paper. Most movements, except lateral flexion, could be represented by Euler angles when the order of rotation was flexion/extension-lateral flexion-axial rotation. For lateral flexion the order flexion-axial rotation-lateral flexion had to be used (Hof et al., 2001). A recent study (Crawford, 2002) suggested that the tilt/twist method (Crawford et al., 1999) should be preferred as it enabled an angular representation for all movements of interest.

2.5. Experimental protocol

For the experiments the subjects sat on a chair. The protocol consisted of five different types of rotation:

axial rotation to left and right in the erect position, axial rotation with maximally extended neck, axial rotation with maximally flexed neck, flexion-extension, and lateral flexion to left and right (Dvorak et al., 1992). To assess the reliability each movement was repeated eight times. The whole protocol was performed both actively and passively. In the assessment of the active range of motion the subject was asked to rotate as far as possible. Transducer positioning, landmark palpation and passive motion were all done by the same observer, a physician. In five subjects the measurements were repeated twice, in the other five subjects they were repeated four times, three times at least four weeks apart, while the fourth session was within 1 h after the third one. Between sessions three and four the transducers were repositioned and the stylus measurements were repeated.

To test the accuracy of the measurement system a 'dummy head' was used (Hof et al., 2001), consisting of a revolving cylinder ('head') mounted on a plateau which could be tilted to simulate flexion/extension or lateral flexion.

To assess whether there was an increasing or decreasing trend in a series of 8 consecutive measurements a sign test was used. Test quantity was the difference between the mean of the first four and the last four measurements. The difference between active and passive measurements was tested with a Wilcoxon ranked-sign test. The significance threshold was in both cases set at 1%.

3. Results

In the *dummy measurements* axial rotation, forward flexion, and lateroflexion were reproducible within 0.85° (SD, from ≈50 measurements at intervals of 10°, see Hof et al., 2001). When axial rotation is performed together with maximal flexion or extension, a systematic error between ±1.7° is found in addition, due to crosstalk from the flexion or lateral flexion. An axial rotation of 120°, on the other hand, resulted in a crosstalk up to 14° in the flexion and lateral flexion angles. This is an effect of the angular representation of the rotation (Hof et al., 2001; Hof and Winters, 2002).

Within a series of eight consecutive measurements on human subjects the standard deviations ranged between 2° and 4° (Table 2, first column). There was no significant increase or decrease of the range of motion in the series of eight repeated rotations (sign test, $n = 80$, $P \leqslant 1\%$). Active and passive measurements did not show systematic differences (Wilcoxon ranked-sign test, $P \leqslant 1\%$), except for axial rotation, in which case it amounted to 4.4° average. Between sessions there could be considerable differences, much more than to be expected from the SD within sessions, see SD values in Table 2, col. 3. These differences between sessions were not caused by long-term changes in the subjects, because the differences between two sessions within 1 h were of a similar magnitude, Table 2, column 2.

Table 2
From left to right: standard deviation of a single series of measurements, differences between two measurements on the same day (within 1 h), and between measurements on two days at least four weeks apart

	Series SD (deg.)	Same day SD (deg.)	Between days SD (deg.)
Axial rotation	2.2	4.0	5.1
Axial + extension	4.2	12.6	11.8
Axial + flexion	3.1	15.5	10.5
Flexion-extension	2.6	8.6	9.6
Lateral flexion	1.7	6.8	11.6
n of subjects	10	4	5

Unit: degrees. SD's are mean values for n subjects and $4n$ measurements (active/passive, left/right).

4. Discussion

The principal objective of this study was to verify the accuracy of the FoB system in measuring neck rotation. The second aim was to obtain data on the variability and reproducibility of the range of motion for neck rotation in a group of healthy subjects.

4.1. Accuracy of the instrument

The measurements with the dummy head indicate that the FoB is an accurate measurement system for neck movement with a maximal error of ±2.5° over a range of 180°. This includes both a random error and a systematic error due to cross-talk of about 0.7° and ±1.5° respectively. The random errors are comparable to those reported from other measurement systems: ultrasound (Dvir and Prushansky, 2000), electromagnetic (Day et al., 2000) or electrogoniometer (Feipel et al., 1999). The crosstalk errors, also reported by other authors (Feipel et al., 1999; Feipel et al., 2001), are due to slight and unavoidable misalignment between the LCS coordinate axes and the anatomic axes of rotation. They are influenced by the mathematics of the angular representation, but independent of the method of measurement.

A possible source of error is movement of the thoracic receiver due to breathing. It was verified that angular motion was less than 0.5° in any direction during quiet breathing.

4.2. Variations within subjects

Within the same session, the standard deviation of the ranges of motion was small: 2–4° (Table 2). This has the practical consequence that it is not necessary to make a large number of measurements to achieve a reliable estimate of the range of motion. In many cases a single measurement may suffice, an alternative is to take the average of three measurements. It might be expected that repeated determination of the ranges of motion could result in an increasing tendency, a kind of accommodation of neck motion to exercise, but no such effect was found. A systematic difference between active and passive measurements could in this study only be demonstrated for axial rotation, but it amounted to only 4.4° on average. In literature there is no unanimity on this point. Dvorak et al. (1992) state that 'it is well established that a passive examination results in a larger motion', but this is not clearly reflected in their results, which show a just significant difference in only three out of five movements. Chen et al. (1999) could not confirm this claim in their meta-analysis of 45 papers.

While variability was small within the same session, it could be considerable between sessions. For purely axial rotation the standard deviation was limited to about 5°, but for the other rotations it amounted to about 10° (Table 2). If the measurements are normally distributed, this means that differences of up to 30° could occur between sessions. This was indeed found: in 100 repeated measurements 10 times differences between 25° and 30° were observed between sessions in the same subject. For a discussion, see Bogduk and Mercer (2000).

4.3. Practical aspects

As stated in an earlier review (Chen et al., 1999), the specific instrumentation has no major influence on the outcome of cervical range of motion measurements. The achievable accuracy of most systems is well within the biologic variability, and not greatly different. The FoB system has proved to be a practical system. The sensors are small, $2 \times 2.5 \times 2.5$ cm, and in spite of the cable connections the encumbrance of the subjects is minimal. Disadvantages of electromagnetic sensors are that the measurement space is confined to a short distance from the (standard range) transmitter, that it should be free of magnetic materials and that an extensive calibration is necessary. The latter aspect implies that the system is not portable in practice.

Most of the other studies on cervical rotation have just recorded the rotation between two transducers, while we have made the effort to relate the rotations to LCSs fixed to the head and thorax and defined by means of bony landmarks (see Section 2). This method has the principal advantage that the neutral position and the orientation of the axes of rotation are unambiguously defined and are not dependent on the accidental positioning of the transducers and of the subject in the chair. The advantage seems mainly theoretical, as a comparison of our mean range-of-motion data (not reported here) with literature data (Chen et al., 1999) did not yield marked differences between our method and alternative ones. For pathological cases, where a marked asymmetry may be present, there may be a benefit, however. The bony landmark method can equally well be applied in other electromagnetic, ultrasonic or optical measurement systems. Of course, the method introduces an error of its own, due to measurement errors in the determination of the landmarks. In a small sample of six measurements we processed the same measurements with two different bony landmark measurements. It turned out that the errors were between 2° and 4°. This relates only to errors in the neutral position; the total range of motion (e.g. from extreme left to right) is not affected.

5. Conclusions

Table 3 summarises the order of magnitude of the various sources of variation in the measurements, as discussed above. When applying the method in clinical practice, our findings suggest some simple measures.

(1) After proper calibration, the FoB system is fully adequate for measuring 3-D angles. Used in the proposed way, it gives minimal encumbrance of the subjects and is not dependent on the precise maintenance of posture.
(2) Due to crosstalk, rotations around non-dominant axes cannot be determined with confidence. This is

Table 3
Schematic overview of measurement errors in cervical range of motion assessments with the FoB system

	Error (deg.)	Nature of error
Instrument	1 (r.m.s.)	Random
Crosstalk	<1.5 (max.) dominant axis 12 (max.) non-dominant axis	Systematic
Bony landmarks	3 (r.m.s.)	Systematic per session Random between sessions
Variability within session	2 (r.m.s.) simple 4 (r.m.s.) combined	Random
Variability between sessions	5 (r.m.s) axial 10 (r.m.s.) simple 15 (r.m.s.) combined	Random (?)
Individual differences	5–15 (r.m.s.)	Random

Data on crosstalk are in (Hof et al., 2001; Hof and Winters, 2002). Error in bony landmark palpation is an estimate.

a mathematical problem, not related to measurement methodology (Hof et al., 2001).
(3) The biological variability within a measurement session is relatively small. As a result, in many cases a single measurement may suffice. When greater precision is required, it might be suggested to determine the mean of three measurements.
(4) The palpation of the bony landmarks should be performed scrupulously.
(5) It should be considered that there can be considerable differences, up to 10° SD (30° maximum) between different sessions, not related to pathology. This effect is minor (SD 5°) in pure axial rotation, more serious in flexion-extension and lateral flexion (SD 10°) and most pronounced in the combined rotations (SD up to 15°).

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